SOME CHARACTERISTICS

OF

CRYSTAL DETECTORS

By

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and

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OUTLINE

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The purpose of this research is the investigation of the behavior of certain crystal detectors, as used in wireless telegraphy, when subjected to varying conditions of temperature, pressure and humidity.

Considerable work has been done in recent years in studying the properties of various crystals and metals which have been found to be rectifiers of high frequency oscillating currents. That is, when an alternating or oscillating current is impressed, they permit a considerable current to pass in one direction and only a small or often negligible current in the other. Among the more important of the early investigations was the work of G. W. Pickard[(1)] who discovered that a contact between silicon and copper had rectifying properties. In 1907 L. W. Austin[(2)] described detectors using contacts of tellurium with aluminum and also tellurium with silicon.

(1) Electrical World XLVIII, p. 1003, 1906.

(2) Physical Review 24, 508, 1907.

G. W. Pierce carried on a series of investigations into the action of a number of contact detectors. In 1907 [3] he published the results of a study of carborundum. In this work he impressed various direct current voltages across the crystal, first in one direction and then in the other, and read the resulting currents, finding the crystal to be noticably unilateral in its conductivity. He also impressed alternating current voltages and obtained oscillograph records of the rectified current. He later carried on investigations of anatase, brookite and molybdenite.(4) In addition to experiments similar to those carried with carborundum, he tried to find a relation between the rectification and the thermo-electric current obtained by heating the junction first on one side and then on the other. He found, however, that the thermo-electric was usually in the opposite direction to the rectified current. Further work using iron pyrites as a detector(5) lead him to the conclusion that thermo-electricity and rectification may have a common basis but are not identical phenomena. In his "Principles of Wireless Telegraphy" [6] Pierce concludes, as a result of quantitative

(3) Physical Review <u>25</u>, 31, 1907.

(4) Physical Review <u>28</u>, 153, 1909.

(5) Physical Review <u>29</u>, 479, 1909.

(6) Page 128, 1910 Edition.

experiments, that the heating of the contact due to the passage of the current is far insufficient to account, in a thermo-electric way, for the large rectified current actually produced.

L. W. Austin of the U. S. Bureau of Standards (7) has investigated the action of detectors consisting of silicon-steel, carbon-steel and tellurium-aluminum contacts. His method was (1) to apply a direct electromotive force to the contact, first in one direction and then in the other, and measure the resulting currents on a galvanometer or ammeter. (2) He sent alternating current of 60 cycles through a fall of potential wire and, taking the required voltages from sliding contacts, applied them to the rectifying contact which was in series with a direct current ammeter. He reached no definite conclusion as to the explanation of the phenomona, but makes mention of the fact that "the rectified current flows in opposition to the thermo-electric current produced by heating the contact, except in the case of tellurium-aluminum at low voltages where another phenomenon, possibly thermo-electric, predominates.

Alan E. Flowers (8) makes note of the effect of heat

(7) Bulletin Bureau of Standards 5, 153, 1908.

(8) Physical Review 29, 445, 1909.

upon the rectifying properties of galena. He states that the retification disappears at about 270°C., but is partially regained upon cooling. The direct effect of heat, however, is complicated by the local heating of the flowing current and also by electro-chemical effects. In a later article [9] Flowers states that a "resistance in series with the galena crystal rectifier greatly increases the rectification ratio even for the same potential difference on the terminals of the rectifier". In an article on crystal rectification [10] Flowers states that (1) frequency of alternations has little effect on the galena detector and (2) the current density at the contact is the electrical quantity of chief importance.

Shunkichi Kimura, [11] while not stating what crystal contact he was using, said that one explanation of the action is by rectification but "in mineral detectors some much more complicated action is suspected, though it takes no definite shape, So far as known all forms of present detectors possess the property of polarity, whether electric rectification or magnetic hysteresis. The sense of rectification is constant while the potential working on the mineral detectors is large, but where it is small we

(9) Physical Review 3, 25, 1914.

(10) Electrician LXXIV.,Dec. 11, 1914.

(11) Physical Review 34, 356, 1912.

observe reversals, the galvanometer deflecting in opposite senses irregularly and the tone audible in the telephone while the galvanometer shows no deflection at all".

In a paper "On the Conduction of Electricity at Contacts of Dissimilar Metals" (12) R. H. GODDARD describes his method of measuring rectification by applying a direct current first in one direction and then in the other, the time of each application being long enough to take a reading of the current. He used combinations of carbon, tellurium, galena, silicon, magnetite, magnesium, aluminum, zinc, copper, iron, silver, tin, lead and platinum. He studied the effects of large currents, high vacua and various surrounding gases. The conclusion Goddard reached was that "rectification was of two kinds, 'surface' and 'body' rectification; that the former takes place with pure elements in an active gas, and the latter with impure elements and chemical compounds, irrespective of the nature of the gas present".

Ralph C. Hartsough, (13) of the University of Kansas, carried on a research to obtain a contact which would be suitable for the rectification of heavy currents and which would be unaffected by varying physical conditions. After

(12) Physical Review 34, 423, 1912.

(13) Physical Review 4, 306, 1914.

an exhaustive search he chose a silicon-carbon contact which he found was unaffected by changes in temperature or air pressure.

EXPERIMENTAL WORK

Up to the present time the phenomenon of contact rectification has been investigated by the direct application of known potential differences, both direct and alternating, at the terminals of the rectifier. Since the most important use of crystal rectifiers at the present time is in wireless telegraphy, it was decided in this research to undertake the investigation of the properties of four of these detectors as commonly used in actual practice. The detectors studied were galena, perikon, silicon and carborundum. For this purpose we erected a sending station and a complete receiving station in different parts of the building. By this means we were able to study the practical working efficiency of the detectors as we varied the physical conditions.

For sending we used a 1 K.W. Type H-2 Thordarson transformer using 110 volts, 60 cycle alternating current and giving 20,000 volts at the secondary terminals. The condenser was made of glass plates and tinfoil immersed in oiland was of .026 mf. capacity. The oscillation transformer consisted of two helices of the pancake type inductively coupled and arranged so that the coupling could easily be varied. A rotary spark gap was used giving a spark frequency of 600 per second. The aerial was a helix 62 cm. in diameter consisting of 18 turns of No. 16 copper wire spaced 10 cm. apart and was hung from the ceiling of the room where the sending station was located. In order to increase the wave length we added a loading coil 25cm. square consisting of 17 turns of No. 14 copper wire spaced 2.5 cm. between turns. This gave a wave of approximately 500 meters. The ground connection was made on a water pipe. Fig. 1 shows the diagram of connections.

The aerial used for receiving was a helix 90 cm. in diameter consisting of 18 turns of No. 4 copper wire spaced 16 cm. between turns. It was hung under the peak of the roof of the building at a distance of about 90 ft. from the sending aerial. A lead wire of No. 4 copper wire extended down into the basement where the receiving station was located. The distance between the sending and receiving instruments was about 80 ft. Practically all of the received energy came through the helical aerial. This assumption was verified by the fact that when the aerial was disconnected the signals from the sending station became practically inaudible. The ground connection at the receiving station was

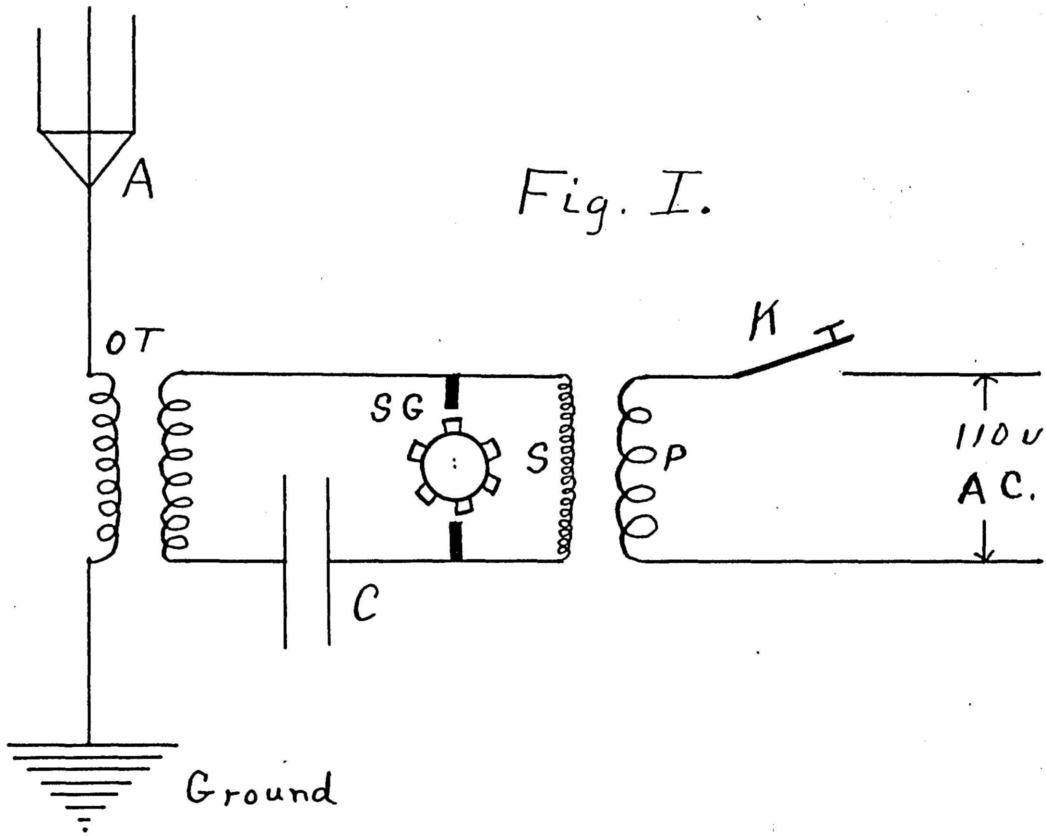


Fig. I.

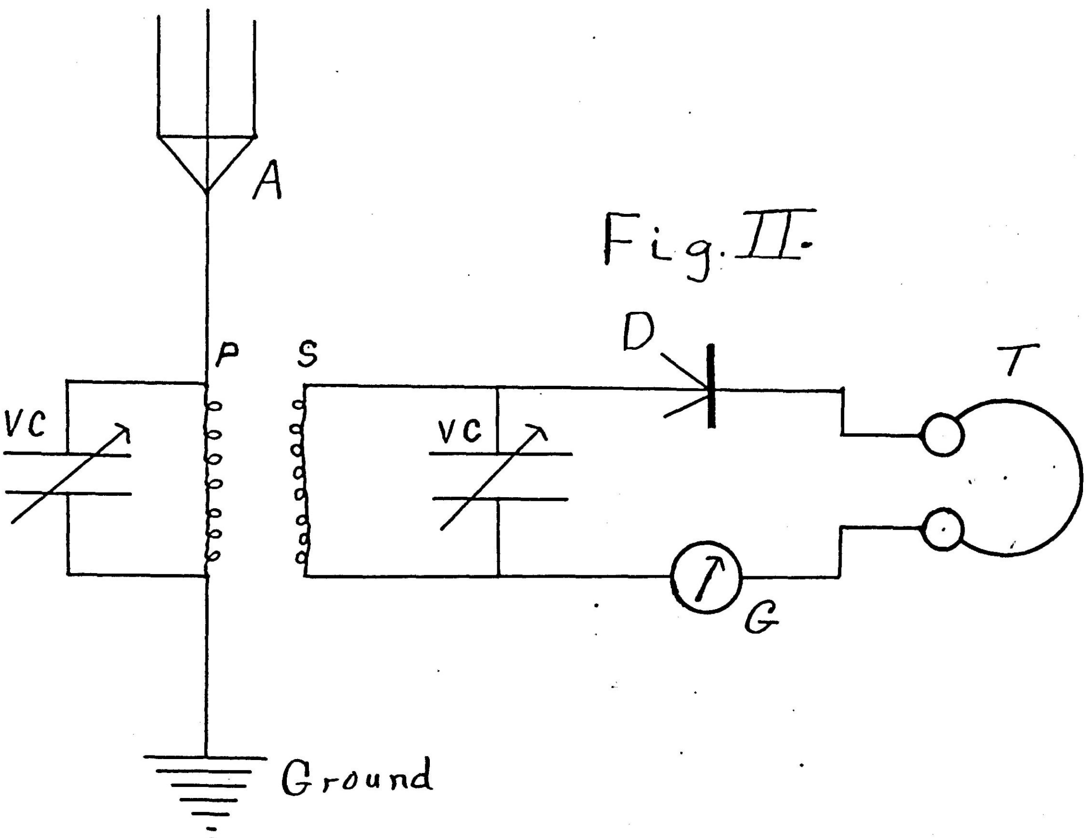


Fig. II.

made to a large iron pipe extending into the ground just outside of the building. A type D Clapp-Eastham, loose coupled tuner was used with variable condensers across both primary and secondary for close tuning. Murdock 3000 ohm telephones were used and the detector stand was typical of those ordinarily used in wireless telegraphy. A Leeds and Northrup ballistic galvanometer of 1060 ohms resistance and with a sensibility of .0026 micro-amperes per millimeter was used to measure the current which passed through the detector. Fig. 2 gives a simple diagram of the instruments as used for receiving.

One of the leads of the primary of the sending transformer was taken through the receiving room and a key inserted there. This facilitated the work by making it possible to control the whole experiment from one point. In order to keep the radiation from the sending station constant during a given series of teste the current in the closed oscillatory circuit was regulated by adjusting the magnetic leakage shunt of the transformer. It was found that our hot-wire ammeter would not indicate the small aerial current which it was neccessary for us to use. To check the constancy of the radiation we therefore inserted the ammeter in the closed oscillatory circuit and kept the inductance, coupling and the position of the aerial always the same. The coupling was very loose to insure a pure wave. The normal current

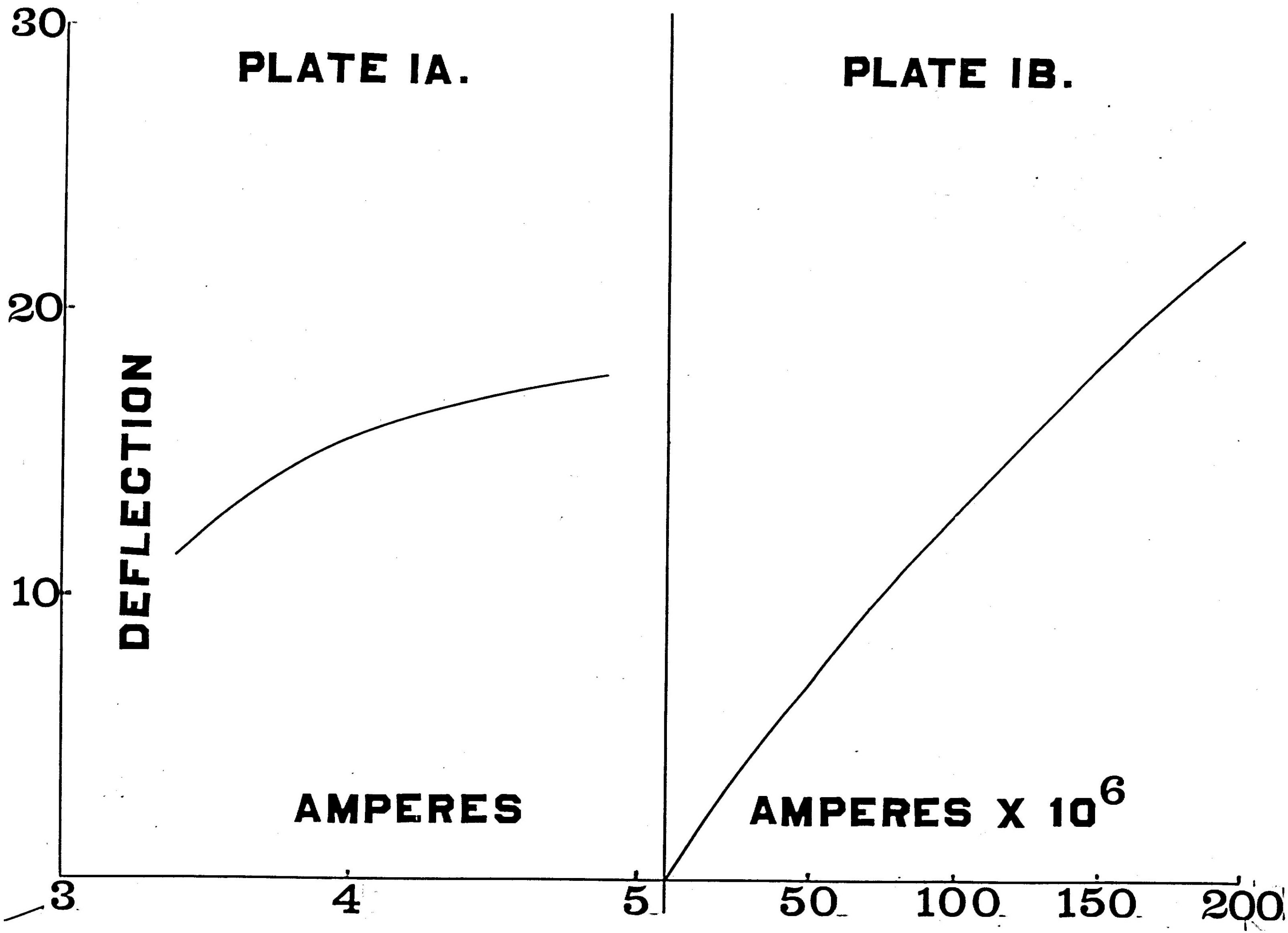
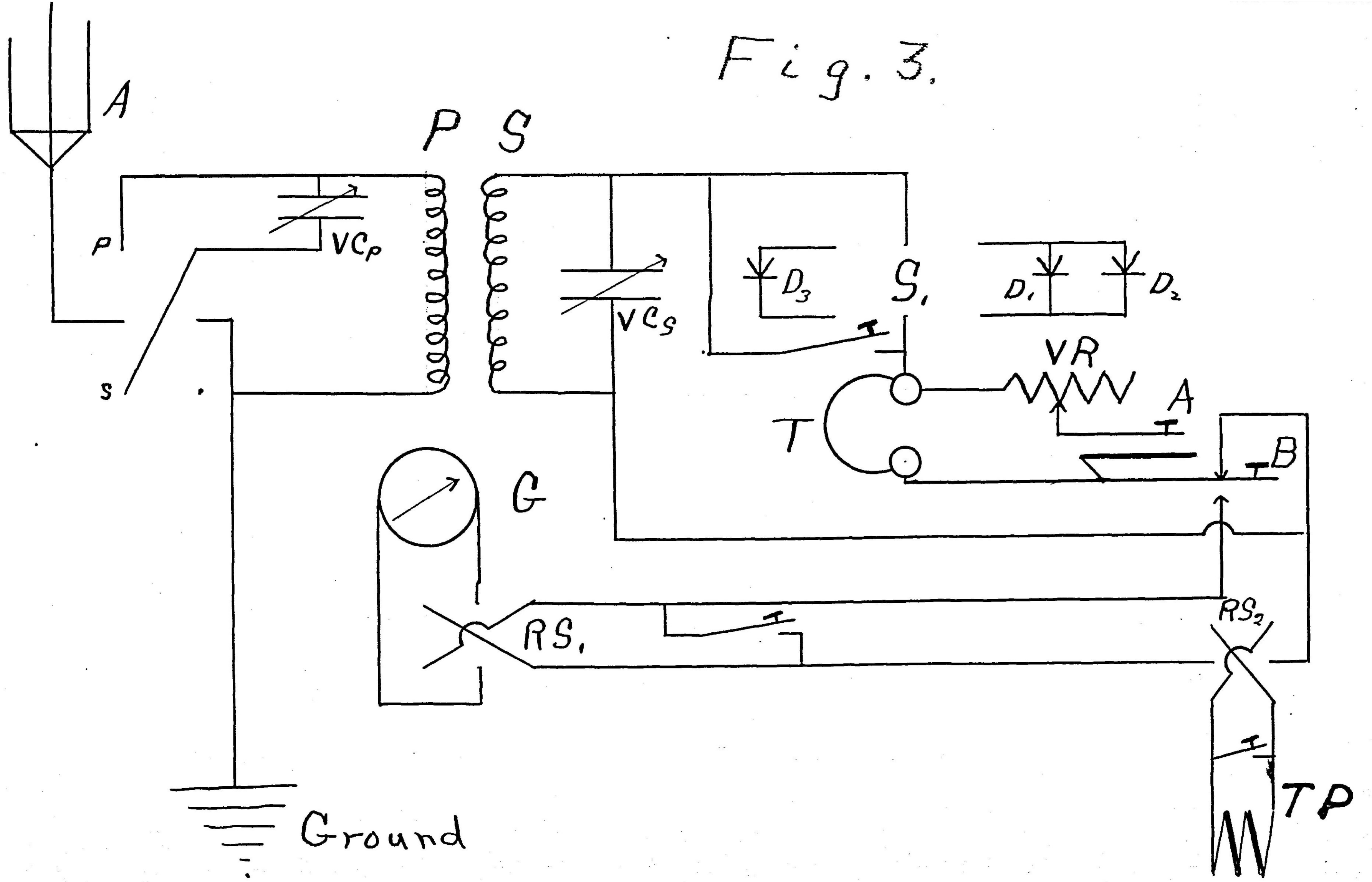


PLATE IA.
PLATE IB.
30
20
10
DEFLECTION
AMPERES
AMPERES X 10^6
3
4
5
50
100
150
200

Fig. 3.



used in the oscillatory circuit was 4.5 amperes, the power consumed by the transformer under these circumstances being 230 watts. It was found that for values in the neighborhood of 4.5 amperes current in this circuit small variations such as neccessarily result from fluctuations in the voltage of the power supply would produce only small variations in the galvanometer deflections. This is shown by the accompanying curve, Plate IA.

Fig. 3 gives the complete diagram of the receiving instruments as used in the research work. The signals were sent out from the sending station by closing the key at the receiving station. By closing the key A shunted telephone readings could be obtained giving the relative strength of the signals in terms of audibility. This method, however, has proven to be unsatisfactory for careful work. We therefore confined our work to the use of a galvanometer, In order to prevent any inductive effect in the galvanometer circ circuit from the make and break of the current in the primary of the sending transformer the key B was always left open at the make and break of the sending key. The length of the signals, however, was determined entirely by the time during which the key B was closed. By means of a reversing switch RS_1 the direction of the galvanometer deflection could be changed. The switch S_1 was used to connect in an auxilliary detector to receive messages from other stations without disturbing the detector under test.

By far the most bothersome source of error which we encountered was an "extra" E.M.F., as we have chosen to call it, which made its appearance continually, to a greater or less degree, throughout the course of the research. It originated at the contact of the detector and would cause an unwarranted deflection of the galvanometer at all times even when no signal was being received. To eliminate this we first tried to insert an opposing E.M.F. in the galvanometer circuit by means of a potentiometer. This arrangement was very inflexible, inconvenient and altogether unsatisfactory. A method was devised, however, which proved to be entirely satisfactory and was very easy to manipulate. It consisted simply of a thermo pile-which we inserted directly in series with the galvanometer. It was heated by the radiation from a thirty-two candle power carbon filament lamp. To adjust the E.M.F. generated by the thermo-pile the proximity of the lamp was varied by a system of pulleys by which the lamp could be moved back and forth on a sliding track. This arrangement made it possible to eliminate entirely all extraneous currents due to electro-chemical or thermo-electric effect such as have been mentioned by Flowers.(14)

(14) Physical Review 5, , 445, 1909.

MANIPULATION.

The following is the method of procedure used in taking a series of readings. One observer confined his attention to the galvanometer. He first eliminated whatever "extra" E.M.F. was present by opposing it with the E.M.F. generated in the thermo-pile. Since the "extra" E.M.F. often reversed its direction it was neccessary to use a reversing switch RS_2 in order that the E.M.F. of the thermo-pile might always oppose it. This balance was secured by closing the key B and adjusting the distance of the lamp until the galvanometer showed no deflection. A great convenience in this adjustment was the use of two keys, one to short circuit the thermo-pile and the other to short circuit the detector. By this means we were able to determine separately the effect of each of the two sources of E.M.F.

The observer in charge of the galvanometer wore the telephone receivers at all times so as to detect any errors in the readings which might occour due to the interference of static or the sending of nearby stations and all data containing such errors was thrown out.

The other observer then closed the sending key which puts the sending station in operation and, with stop watch in hand, pressed the key B for a certain length.of time. A signal of three seconds duration was used almost exclusively during this research. As will readily be seen we were using the galvanometer neither ballistically nor as an ordinary current galvanometer. Because of its long natural period it did not have time to come to its full deflection during the three seconds for which the current was flowing through it. The accompanying calibration curve Plate IB, shows the deflections produced by the corresponding currents flowing for a period of three seconds. The second observer then opened the primary key and recorded the data regarding the particular physical conditions in operation. Meanwhile the first observer has recorded the deflection of the galvanometer and is again checking up the balance of the "extra" E.M.F. During the progress of the research this operation was repeated over 3000 times.

We did not attempt to secure the most sensitive adjustment possible when making a test but tried above all to secure one which would remain permanent and which gave a clear, uniform tone. The deflections were adjusted to the range of the galvanometer scale by varying the coupling of the receiving transformer which was then kept the same throughout any one experiment.

In order to subject the detector to the various physical conditions desired, we had constructed what we called a "pressure box." It is shown at A, Fig. 4. It consists of a battery cell about 4 inches cube with a cover

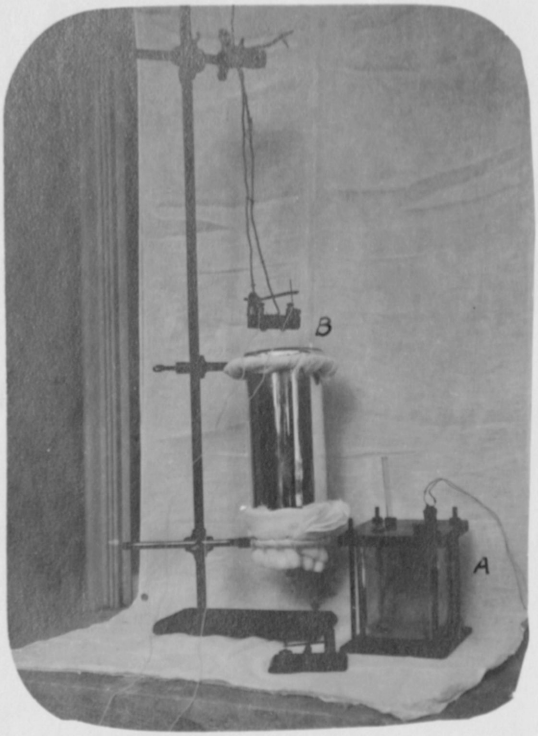


Fig. 4

of half-inch brass held to a brass base by a brass rod at each corner. A rubber gasket was placed between the cover and the rim of the jar in order to insure an air-tight contact. Four half-inch holes in the cover permitted the insertion of thermometers, lead wires and air tubing.

To heat our detector we inclosed it in the "pressure box" which was then immersed in cylinder oil of a high flash point and heated by a gas burner. In order to cool the detector we suspended it in an U-shaped Dewar flask which contained liquid air. This arrangement is shown at B, Fig. 4. The temperature obtained was measured by means of a pentane thermometer.

The pressure in the "pressure box" was varied by means of a motor-driven air pump and measured by an open-tube manometer.

The humidity of the air in the"pressure box" was varied by varying the concentration of sulphuric acid contained in the bottom of the box. The air was first dried by putting a known volume of concentrated sulphuric acid in the bottom of the box and letting it stand for some time. To increase the humidity the acid was diluted by the addition of known quantities of water. The humidity was allowed to reach a state of equilibrium in each case.

The vapor pressure for each concentration was obtained from data given in the Physikalisch-Chemische Tabellen of Landolt, Bornstein and Myerhoff, P. 166, Edition 1905.

RESULTS

Galena

The first physical condition with which we experimented was that of temperature, since it was natural to suppose that changes in temperature would produce the most noticable effect. The galena detector was carefully adjusted and placed in the"pressure box" which was then immersed in oil and heated. The readings were then obtained according to the manipulation previously described. The heat was applied continuously and the galvanometer readings taken at successive intervals, during the rise of temperature. The galvanometer readings were then plotted against the successive temperatures. Plate II, shows one of these curves and is typical of those obtained with galena. On this as well as the other plates the dotted lines indicate results obtained with other specimens or adjustments. The rectification falls off very rapidly with the rise in temperature approaching zero at about 170°C. Upon cooling there was no improvement in the rectification as long as the adjustment remained the same.

The decrease in rectification was not due to increased

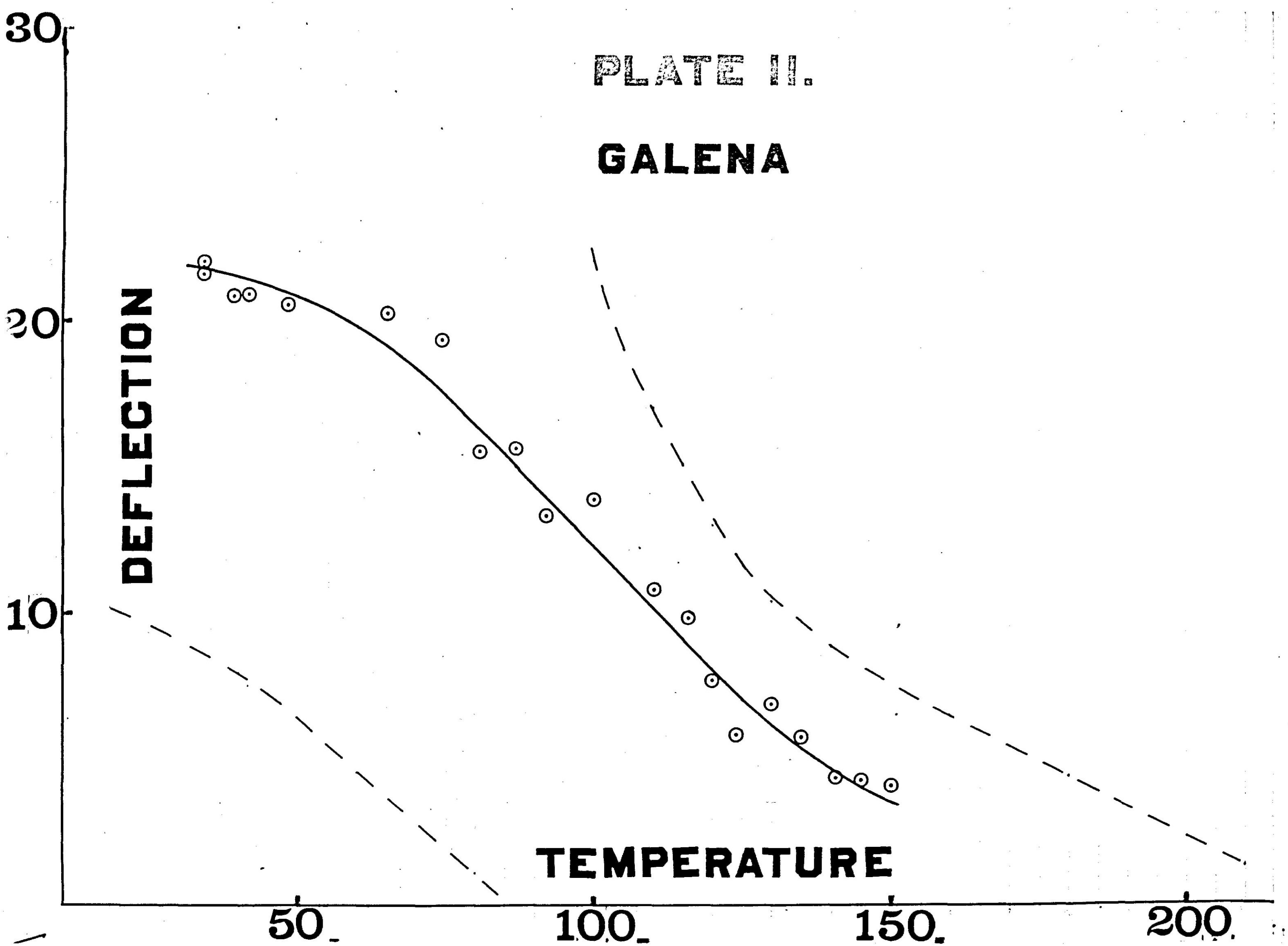


PLATE II.
GALENA
DEFLECTION
TEMPERATURE
30
20
10
50
100
150
200

pressure at the contact since the needle point was suspended by a very fine coil spring so that expansion due to increased temperature would not affect its action. We were much gratified with the uniformity of the readings which we were able to secure with galena since we had feared that, due to the very light contact neccessary, a permanent adjustment could not be retained. The following data shows the uniformity of the galvanometer readings under constant conditions at the detector. These figures also include whatever may have occoured in the time during which the key B was pressed.

Galvanometer deflections for signals 3 seconds long.

Galena detector under room conditions.

15.1
14.6
14.9
15.2
15.0
15.0
14.9
14.9
15.3
14.7
15.0

One noteworthy fact in connection with the rectification of galena is that— although in most cases the current flows from crystal to point, it was found that, with certain adjustments, the current would flow in the opposite direction, namely, from point to crystal.

It is a well known fact that when a large current caused either by a heavy discharge of static or the spark at a sending station nearby, passes through a galena detector, the rectification is impaired. It has occoured to us that a probable explanation of this phenomenon is the local heating of the contact producing an effect similar to the heating described above.

The temperature at which rectification becomes practically negligible is not always the same but varies with the original adjustment, being higher for better adjustments.

The results obtained by heating a galena detector were so marked that we thought it would be highly profitable to investigate the effect of cooling it to a low temperature. The manipulation was by no means as easy as in heating, for we could not obtain the decrease in temperature as uniformly as we should have liked. By lowering the detector nearer and nearer to the surface of the liquid air in the Dewar flask we were able to obtain sufficient data to determine the general behavior of the galena detector in that range of temperature. Plate III. shows the results of this experiment. It will be noticed that at about -50°C. there occoured a decided maximum of rectification which was corroborated by successive tests.

One of the greatest difficulties we encountered in cooling galena as well as the other detectors was the precip-

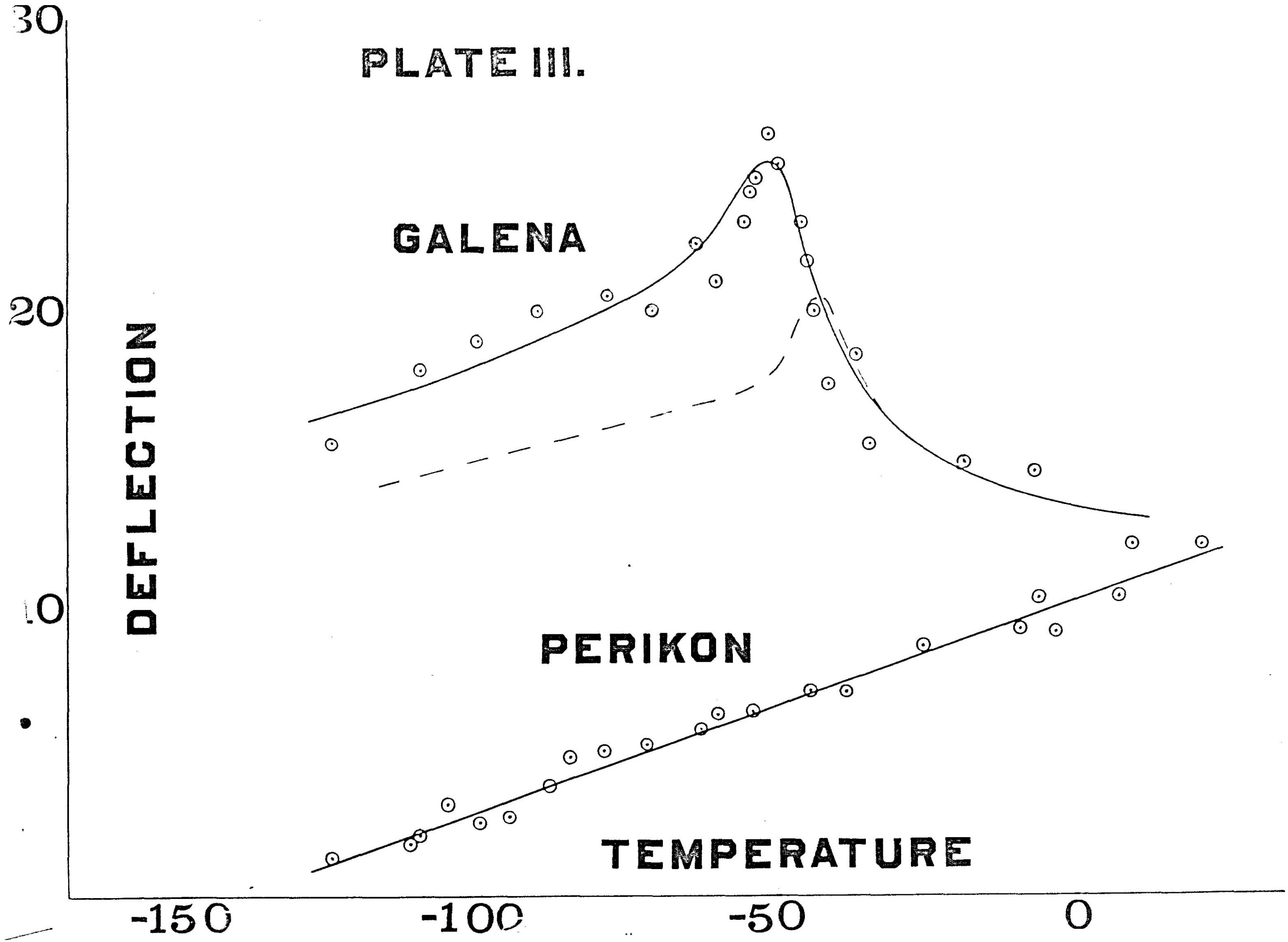


PLATE III.
GALENA
PERIKON
DEFLECTION
TEMPERATURE
30
20
10
-150
-100
-50
0

itation of frost upon the crystal. If any of this frost melted due to heating at the contact the effect of humidity would be superimposed on that of temperature. In addition this moisture at the contact had a decided influence on the "extra" E.M.F. causing it to be very strong, though sometimes in one direction and sometimes in the other. The glass-hardness of the surface of the crystal at these low temperatures made it very difficult to retain the adjustment. It will be noted that the curve obtained by cooling continues the general trend of the one obtained by heating.

We thought it would be interesting to note the effect of completely immersing the detector in liquid air but could find no effect on the rectification of galena by so doing. Good adjustments stayed good and poor ones remained poor.

The results of varying the humidity of the air in the "pressure box" are shown on Plate IV. It will be seen that the presence of a very small quantity of moisture is sufficient to reduce greatly the efficiency of rectification of the galena detector.

Perikon.

The perikon detector used consisted of a contact between crystals of zincite and chalcopyrite. The effect of heat was more marked in the case of perikon than with any

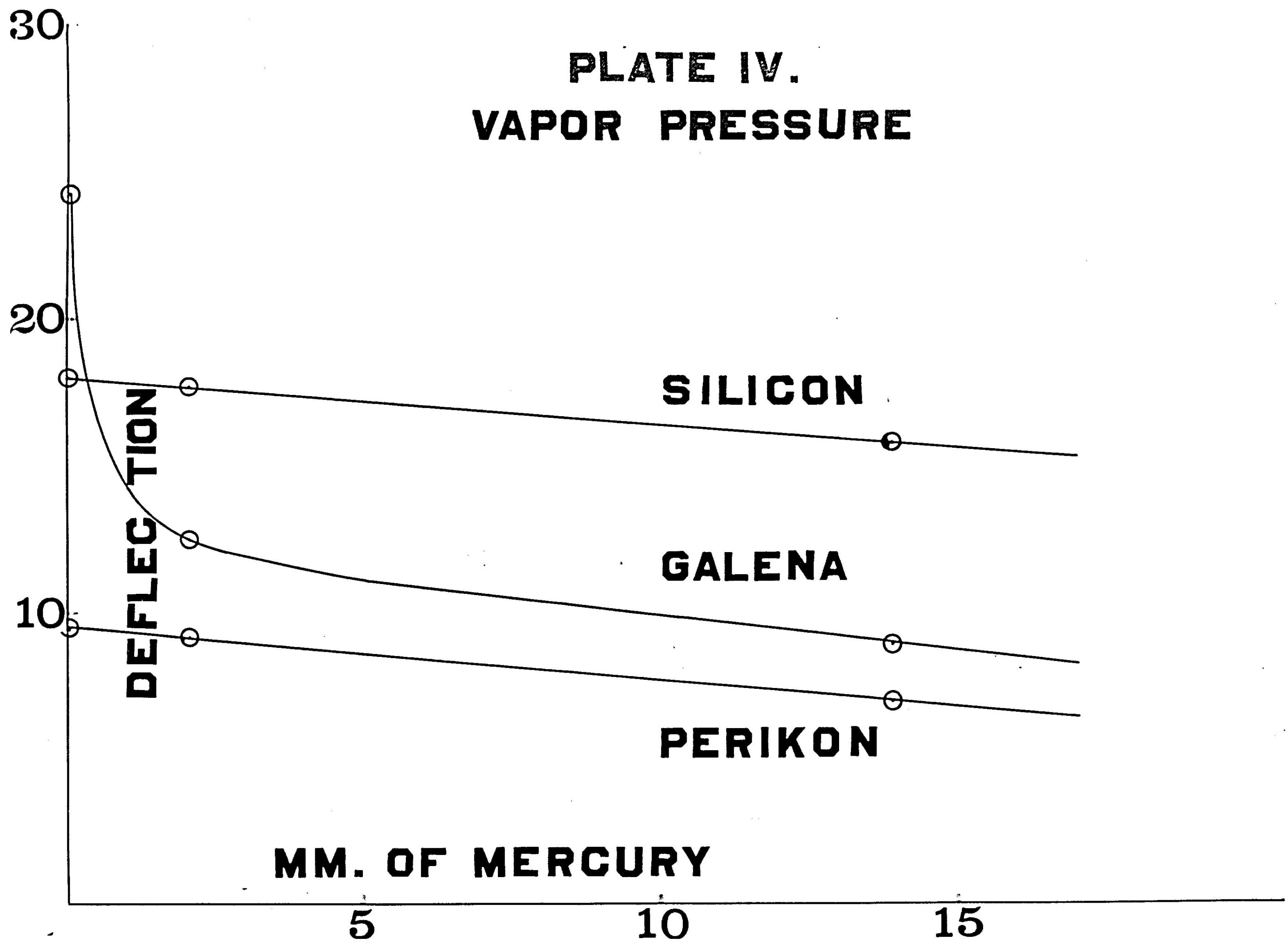


PLATE IV.
VAPOR PRESSURE
30
20
10
SILICON
GALENA
PERIKON
DEFLECTION
MM. OF MERCURY
5
10
15

other detector as is shown on Plate V. Starting with a deflection of three cm. at about 55°C. for a three second dash the deflection passed off the scale of the galvanometer at a temperature of about 140°C. By shortening the length of the dash to one second the deflection became seven cm., but rapidly rose with the temperature reaching a value of twenty four cm. at 210°C. which as far as the experiment was carried. Although the slight drop in rectification shown in the region 20°C. to 50°C. did not appear in all our tests, in this instance it serves to show that the remarkable increase in rectification cannot be due to any change in adjustment because of expansion of the parts of the detector stand upon heating. The rest of the curve, however, is typical of the increase in rectification shown by all our tests in heating the perikon detector.

The curve obtained upon cooling the perikon detector (Plate III) was perfectly continuous with the heating curve, decreasing rapidly with the temperature; and at no time was there apparent any indication of a definite maximum or minimum of rectification within the temperature range which we used, from -120°C. to 210°C. Immersion of the perikon detector in liquid air causes a complete loss of rectification.

Upon subjecting the perikon detector to various degrees of humidity the results shown on Plate IV. were obtained.

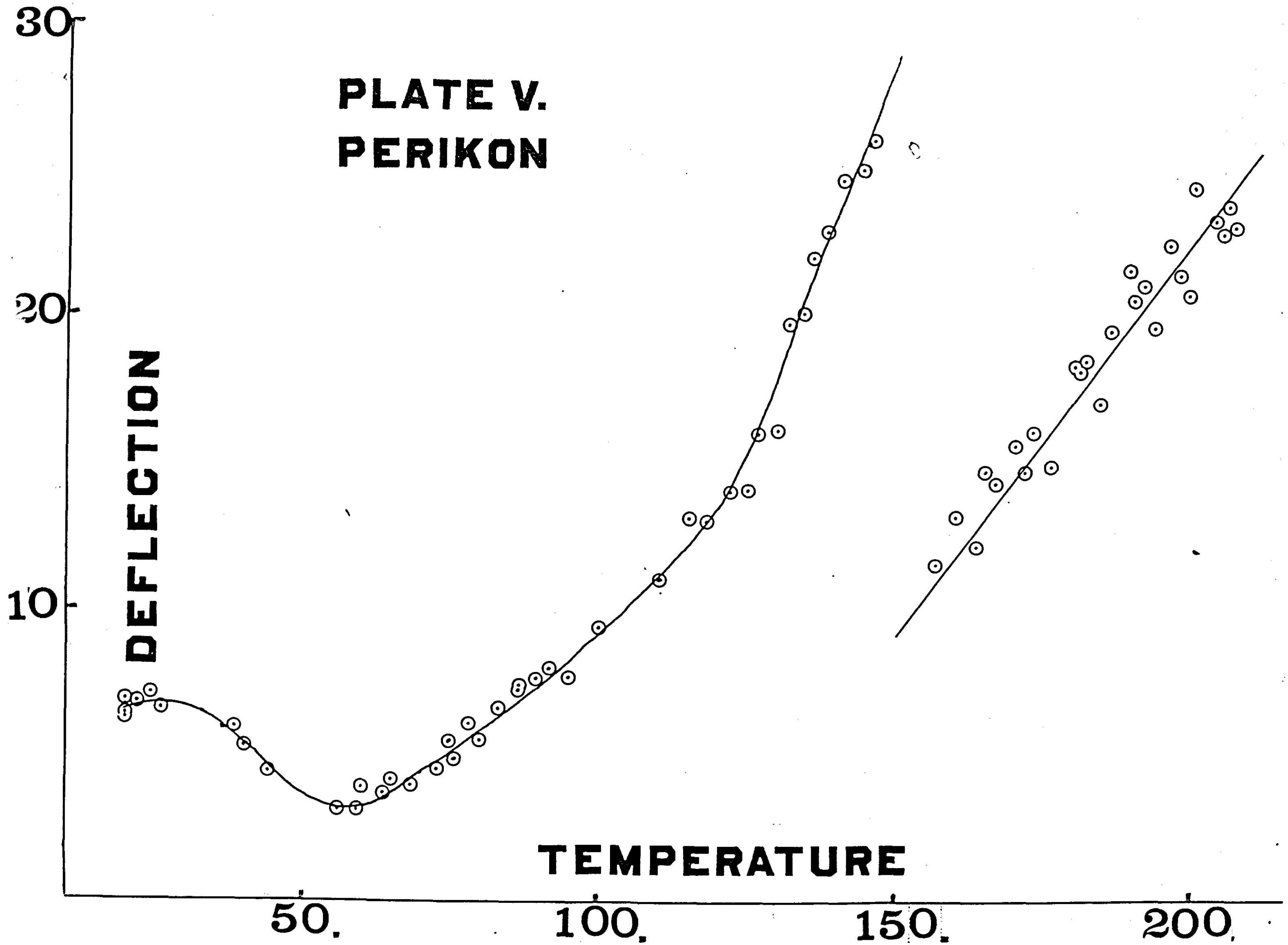


PLATE V.
PERIKON
DEFLECTION
TEMPERATURE
30
20
10
50.
100.
150.
200.

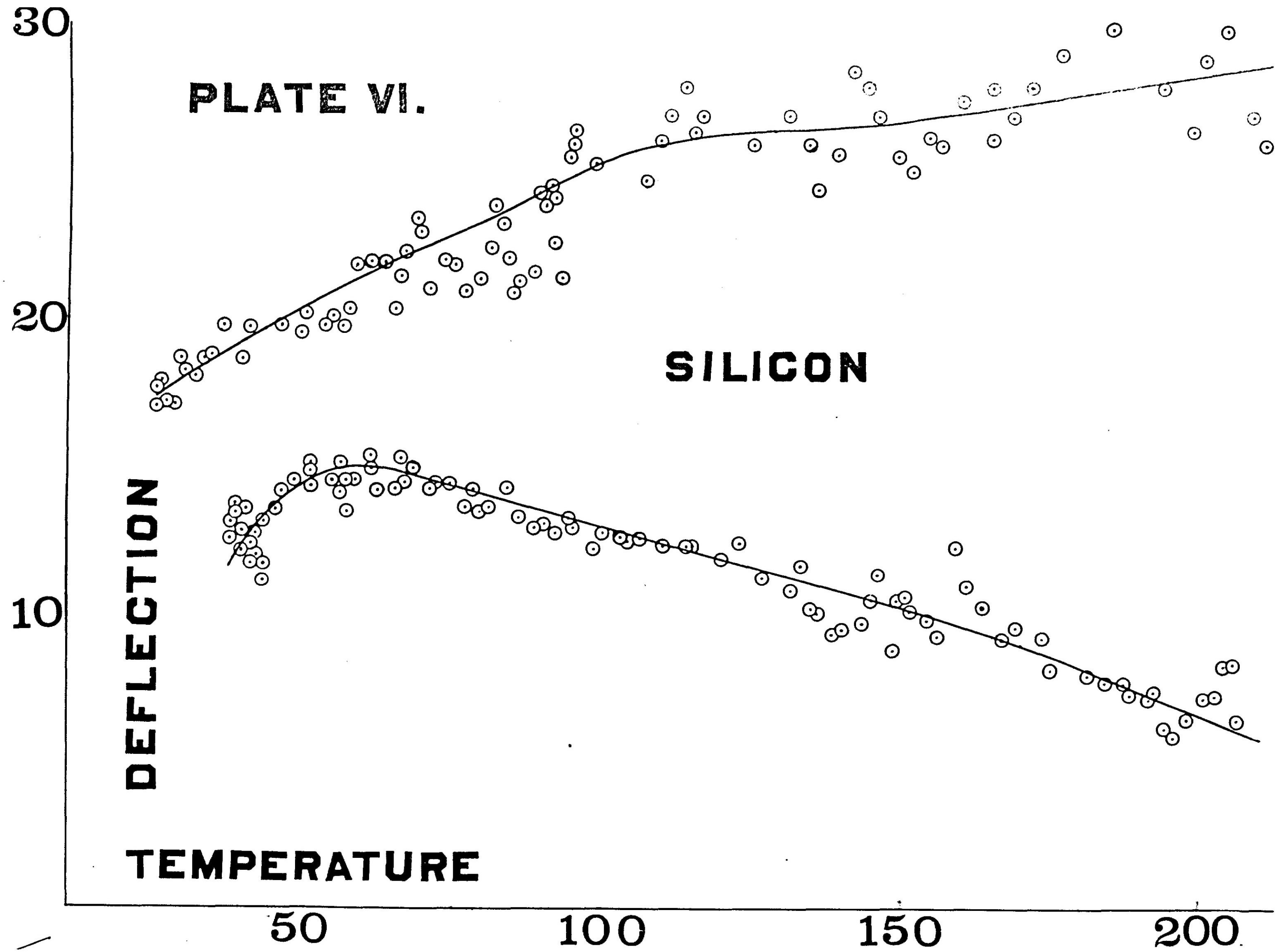
The effect was not so marked as in the case of galena but there appeared a definite decrease in rectification with an increase with humidity. Each of the points plotted on Plate IV. represents the average of at least ten successive readings taken after the vapor pressure had reached a condition of equilibrium.

Silicon.

We found the rectifying action of silicon to be very erratic. This corresponds with the statements made by other observers in regard to the properties of that substance. Miss Frances G. Wick, in a paper on the "Electric Properties of Silicon"(15) makes the remark that "the position of the element in the periodic system between the metals and the non-metals may explain some of the deviations of its properties from those of the stronger metals".

O. E. Buckley(16) states that, since different specimens, sometimes even if cut from the same piece, may vary widely in their electrical properties, it is important that measurements of different properties be made with the same specimens". His statement is borne out by the results of our observations as shown on Plate VI. The conditions of heating were identical in obtaining both curves except that different specimens were used. In one case the rectification is seen to increase and

(15) Physical Review 25, 382, 1907.
(16) Physical Review 4, 482, 1914.



30
PLATE VI.
20
SILICON
10
DEFLECTION
TEMPERATURE
50
100
150
200

in the other to decrease as the temperature rises.

In attempting to obtain the effect of subjecting the silicon detector to low temperatures it was found impossible to obtain any consistent results. The rectification would change very erratically when there was apparently no cause whatsoever, and it was very difficult to retain a given adjustment since the surface of the crystal became exceedingly hard and slippery at the low temperatures.

When the silicon detector was completely immersed in liquid air the sound in the telephone receivers increased in the majority of cases. It is possible that in the other cases the somewhat violent boiling of the liquid air destroyed the adjustment of the light needle contact.

The behavior of silicon under changes of humidity resembles very much that of perikon, the rectification decreasing somewhat on the increase of vapor pressure. These results are shown on Plate IV.

Carborundum.

In order to secure a good adjustment with carborundum we found it neccessary to use considerable pressure upon the contact point consequently imbedding the point of the steel needle below the surface of the crystal. The adjustment was very permanent and could not easily be impaired by vibration.

Upon heating the carborundum detector very peculiar results were obtained as may be seen on Plate VII. Successive tests showed that a decided maximum of rectification occoured at a temperature of about 130°C. and from there fell off rapidly until a minumum was reached at 165°C. From there the rectification again increased with the temperature as far as the tests were conducted. Even when the glass "pressure box" accidently broke and the detector was immersed in the hot oil bath its behavior remained the same. This is probably due to the fact that the oil could not reach the actual contact between the crystal and the needle.

The cooling curve (Plate VIII.) was equally satisfactory, continuing the lower portion of the heating curve. Rectification became zero at about -85°C. It was noteworthy that upon allowing the detector to warm up it largely regained its rectifying properties which shows that the contact itself had not been disturbed. In order to prove that the decrease in rectification was not due to an imperfect contact caused by the contraction of the needle and detector stand we tried repeatedly to secure a new adjustment at these low temperatures but found it impossible. Likewise immersion in liquid air proved disastrous to all rectification.

It was impossible to obtain any noticeable effect on the rectification of carborundum by cahnges of humidity. We concluded that this, also, was due to the imbedding of

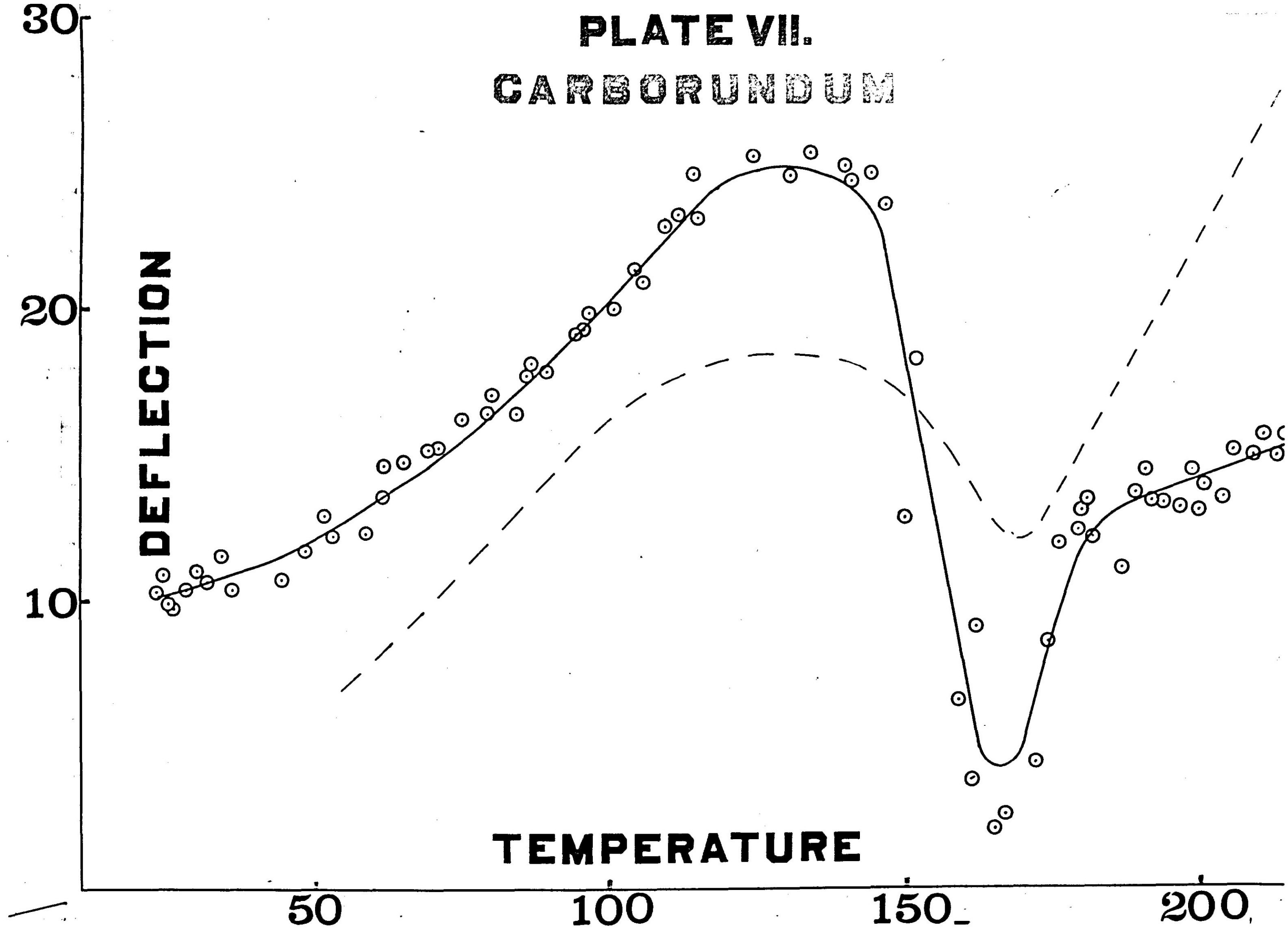


PLATE VII.
CARBORUNDUM
30
20
10
DEFLECTION
TEMPERATURE
50
100
150
200

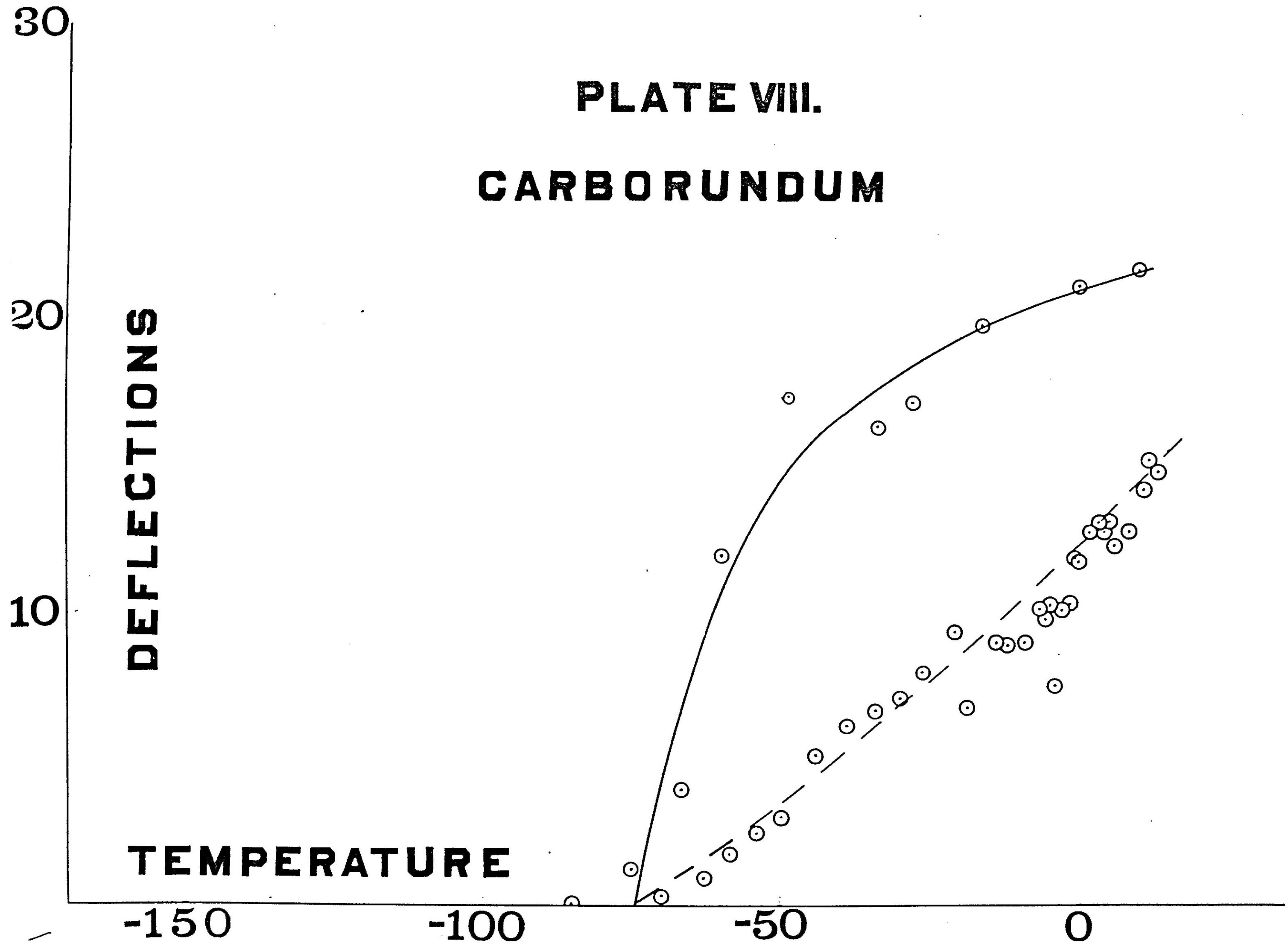


PLATE VIII.
CARBORUNDUM
DEFLECTIONS
TEMPERATURE
30
20
10
-150
-100
-50
0

the contact point in the crystal so that the moisture could not affect it.

DISCUSSION.

It was found that with each of the four detectors, so far as we could observe, changes in air pressure had no effect on the rectification. We were able to vary the air pressure from 25 cm. to 135 cm. of mercury. It is perhaps not surprising that no effect was observed in this range.

One of the peculiarities noticed in our research was that certain crystals did not always rectify the oscillating current in the same direction. With one adjustment the redtified current would flow from crystal to point and with another would flow in the opposite direction. Once, indeed, in making a test on the effect of heat upon carborundum, The direction of rectification actually reversed although no change had occurred in the adjustment. The most common direction of rectification for silicon and for galena was found to be from the crystal to the brass contact which was used. In the case of carborundum the ordinary sense of rectification was in the opposite direction, namely, from needle to crystal. The perikon detector was the only one of the four used which showed no reversal; always rectifying from chalcopyrite to zincite.

The "extra" E.M.F., to which reference has previously been made, is probably of galvanic origin. Although it might have had a thermo-electric origin due to local heating at the contact, it could not have been the result of a thermo-junction caused by the difference in temperature between the detector and the outside circuit since both leads from the detector were of copper, causing the junctions affected by the heat to oppose each other. In addition the frequent reversal of the "extra" E.M.F. precludes all possibility of its being due to a thermo-electric junction.

CONCLUSIONS.

As a result of this research we have not been able to come to any definite conclusion as to the cause of rectification in crystal detectors. However, it seems probable that both a body and a surface effect enter into the phenomenon. The body effect probably predominates in the variations in rectification with change of temperature, while in the case of humidity the surface effect probably has the most influence on the variation in rectification.

At certain times when the rectifidation was especially good a humming sound was heard in the receivers similar to the inductive hum often heard when the detector circuit was opened. This seems to be evidence of the formation of a high-resistance film on the surface of the crystal at the point of contact. Attention has previously been called to the possibility of the presence of this resistance film by Austin (17) and Goddard (18).

There is apparently no relation between the redtification and the "extra" E.M.F. since the former remains unchanged through rapid fluctuations and often reversals of the latter. The "extra" E.M.F. often exists even after room conditions of temperature, etc., have prevailed for some time throughout all the apparatus. The cause of this "extra" E.M.F. and its relation, if any, to the rectification would, in itself, be a profitable subject for investigation.

In conclusion we desire to express our appreciation to Mr. Edison Pettit, of Washburn College, for his helpful suggestions concerning this investigation and to Professor F. E. Kester and the Department of Physics of the University of Kansas for their generosity in providing the special equipment neccessary for carrying on this research.

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(17) Bulletin Bureau of Standards, vol.5, p.146.

(18) Physical Review 34, 423, 1912.

LEW/VAH